InGaAs Multiple Quantum Well Modulating Retro-reflector for Free Space Optical Communications"

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ABSTRACT

Modulating retro-reflectors provide a means for free space optical communication without the need for a laser, telescope or pointer tracker on one end of the link. These systems work by coupling a retro-reflector with an electro-optic shutter. The modulating retro-reflector is then interrogated by a cw laser beam from a conventional optical communications system and returns a modulated signal beam to the interrogator. Over the last few years the Naval Research Laboratory has developed modulating retro-reflector based on corner cubes and large area Transmissive InGaAs multiple quantum well modulators. These devices can allow optical links at speeds up to about 10 Mbps. We will discuss the critical performance characteristics of such systems including modulating rate, power consumption, optical contrast ratio and operating wavelength. In addition a new modulating retro-reflector architecture based upon cat s eye retroreflectors will be discussed. This architecture has the possibility for data rates of hundreds of megabits per second at power consumptions below 100 mW.

Keywords: Multiple quantum well, modulating retro-reflector, free space optical communication

1 INTRODUCTION

Free space optical communication has emerged in recent years as an attractive alternative to conventional RF techniques. This has been due to the increasing maturity of lasers and compact optical systems as well as the inherent advantages of this approach, which include very large bandwidth, low probability of intercept, and immunity from interference or jamming. These features are inherent in the short wavelength of optics, but, to be exploited, require high quality telescopes and extremely accurate pointing and tracking. As a result, optical communication systems can have a large system impact in terms of weight, power and platform stability. Such a system is also inherently complex. These costs are acceptable in many systems, but if the platform is small, or has little available power, the requirements of a conventional optical communications link may be prohibitive.

The low divergence of optics is used in conventional optical communication systems to allow very high bit-rate (~Gbits/sec) links at long range. However, optics low divergence can be used in another way: to enable a new kind of communication system that would be impractical at longer (RF) wavelengths. Rather than using two laser transmitters with their associated gimbaled telescopes and pointing/tracking systems it is possible to establish a two-way optical link using a single

conventional laser transmitter. This transmitter is located on a large platform (or at a ground station) that has sufficient power, payload capacity and platform stability to operate it. It can communicate data to a second small platform conventionally, by modulating its laser with the desired signal. If the laser is strong enough the small platform can receive the data with a detector with a wide field of view, obviating the need for a large pointed receive telescope. However, such a system does not allow the small platform to transmit data back to the large platform. To enable the small platform to send data to the large platform we have examined using a modulating retro-reflector (MRR).

An optical retro-reflector is a passive optical system that reflects light incident upon it exactly back along its path of incidence. Retro-reflectors typically have a large field of view (about 20 degrees full angle) and very high efficiency. Retro-reflectors can be mounted in a hemispherical array to expand the field of view to as large a value as desired. A typical retro-reflector consists of three mirrors mounted in the shape of the corner of a cube. Optical retro-reflectors have been used in recent years to allow millimeter accuracy laser ranging of satellites.

Retro-reflectors can also act as optical communication systems. By mounting an electro-optic shutter in front of the corner-cube, the retro-reflected beam can be turned on or off (or at least modulated). By mounting a modulating retro-reflector on the small platform we can enable it to transmit data, without using a laser or pointer-tracker, to the large platform. In operation, the large platform would illuminate the small platform with a continuous-wave (unmodulated) laser beam. This beam would strike the modulating-retro and be passively reflected back to the large platform. The shutter would then be turned on and off with an electrical signal that carries the small platform s data. This impresses the data stream upon the retro-reflected beam, which then carries it back to the large platform. Fig. 1 shows a schematic of a modulating retro-reflector.
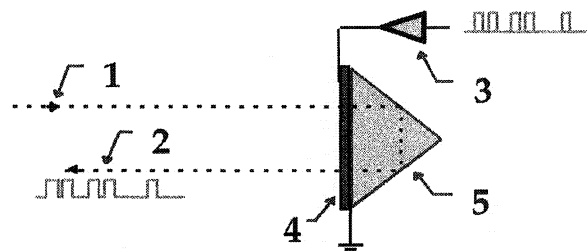

FIGURE 1. Device illustrated where: (1) interrogation beam; (2) reflected modulated beam; (3) driver from the information source; (4) transmissive MQW modulator; and (5) solid retro-reflector.

Such a system can be very light and consume small amounts of power. In addition, if an array is used, the small platform need only be pointed toward the large platform with an accuracy equal to the field of view of the array, which can be 100 degrees or larger. The retro-reflection is insensitive to platform jitter as well. Despite this very generous pointing tolerance on the small platform, the retro-reflected beam has a divergence equal to the diffraction-limit of the retro-reflector (hundreds of micro-radians or less). Thus the small platform maintains the low probability of intercept of a conventional optical communications link, but gains the loose pointing advantage of an omni-directional RF link.

The concept of a modulating retro-reflector is an old one. The impediment to implementation has been the availability of a laser transmitter for the large platform and a suitable shutter for the small platform. The development of conventional optical communication systems has made high quality laser transmitters available. Using such a system there has been a recent demonstration of a modulating retro-reflector link from the ground to a balloon using a ferro-electric liquid crystal as a shutter. This link transmitted data from the balloon at 20 Kbps[1]. Unfortunately, liquid crystal technology is very limited for data transmission. Physically, liquid crystal switching times are limited to data rates of 100 Kbps or less, and even this rate is very hard to achieve.

To extend modulating retro-links to data rates of mega-bits per second and higher, we have pursued the use of a different type of electro-optic shutter: a semiconductor-based optical switch based on GaAs multiple quantum wells (MQW)[23]. Semiconductor MQW technology is the basis for commercially available laser diodes. When used as a shutter, MQW technology offers many advantages. It is robust and all-solid state. In addition it operates at low voltages (less than 20 V) and low power (less than 1 Watt). Most importantly it is capable of very high switching speeds. MQW modulators have been run at data rates as high as 40 Gbps. In practice, for a modulating retro system, the link rather than the modulator limits the data rate. For a conventional corner-cube modulating retro-reflector, MQW technology should allow data rates in the tens of mega-bits per second, depending on range and the laser transmitter on the large platform. Using a new kind of modulating retro-reflector based on a cat s eye optic data rates up to 1 Gbps should be possible.

2. SCALING RULES FOR MODULATING RETRO-REFLECTORS

The characteristics and appropriate applications of a MQW modulating retro-reflector link are determined in part by a scaling rule for retro-reflected optical links

The maximum data rate scales as the strength of the optical signal returned by the link,

$$\frac{P_{laser} \cdot D_{retro}{}^4 \cdot D_{rec}{}^2}{\theta_{div}{}^2 \cdot R^4} \cdot \frac{\left[1 - \dfrac{1}{N_{ext}}\right]^2}{1 + \dfrac{1}{N_{ext}}} e^{-2\alpha L_{MQW}} \tag{1}$$

Where P_{laser} is the power of the laser transmitter on the large platform and θ_{div} is its divergence, D_{retro} is the diameter of the modulating retro-reflector on the small platform, D_{rec} is the diameter of the receive telescope on the large platform, R is the range between the two platforms, N_{ext} is the optical extinction ratio of the modulator, α is the single pass absorption of the MQW in its on state and L_{MQW} is the thickness of the MQW.

The first part of Eq. 1 contains geometric terms affecting the link whereas the latter part contains terms involving the performance of the modulator. The strongest geometric dependencies are on the range and the retro-reflector diameter, both of which scale as fourth powers. Retro-reflector links fall off more strongly with range than conventional links because of their bi-directional nature. The strong dependence on retro-reflector diameter occurs because increasing the size of the retro-reflector both increases the optical power intercepted and decreases the divergence of the returned optical beam. Eq. 1 applies

for space-based optical links. For terrestrial links it applies until the diffraction limited divergence from the retro-reflector is reduced to the limit allowed by atmospheric propagation. When the retro-reflector aperture exceeds this limit the optical power returned scales as D_{retro}^2.

The terms of Eq. 1 involving modulator performance assume a quantum limited receiver system. If the receiver is limited by pre-amplifier noise or other non-shot limited terms then the dependence on modulator extinction ratio will not be as strong.

Given Eq. 1, a strategy for increasing the range or data rate of a modulating retro-reflector link would be to increase the aperture of the retro-reflector. This strategy is limited by the fact that, for a corner-cube modulating retro-reflector, the diameter of the modulator must equal the diameter of the retro-reflector. As we will discuss below the maximum modulation rate decreases and the power consumption increases as the modulator diameter increases. Thus for a corner-cube based modulating retro-reflector any link is a compromise between keeping the modulator small and the retro-reflector aperture large.

3. MQW MODULATOR OPERATING CHARACTERISTICS

3.1 MQW Modulator structure
As shown in Fig. 2 a multiple quantum well modulator is a PIN diode with multiple layers of thin layers of alternating semiconductor alloys in the intrinsic region. These layers consist of a lower band-gap material, the well, and a higher bandgap material the barrier.
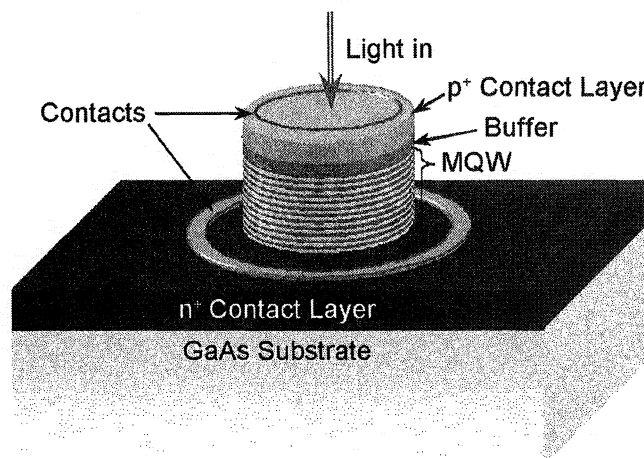

Figure 2. The layer structure of an MQW modulator

Because the semiconductor layers are very thin the conduction and valence bands becomes quantized and the exciton absorption feature at the band-edge becomes narrower in linewidth and enhanced in absorption. The center wavelength of the

exciton is determined by the composition of the well material as well as the width of well. When a reverse bias is applied across the MQW the electric field changes the quantum well potential, shifting the exciton feature to the red and reducing the magnitude of the absorption. Thus, as shown in Fig. 3 a varying voltage on the quantum well is converted into a varying optical absorption over about a 10 nm bandwidth.
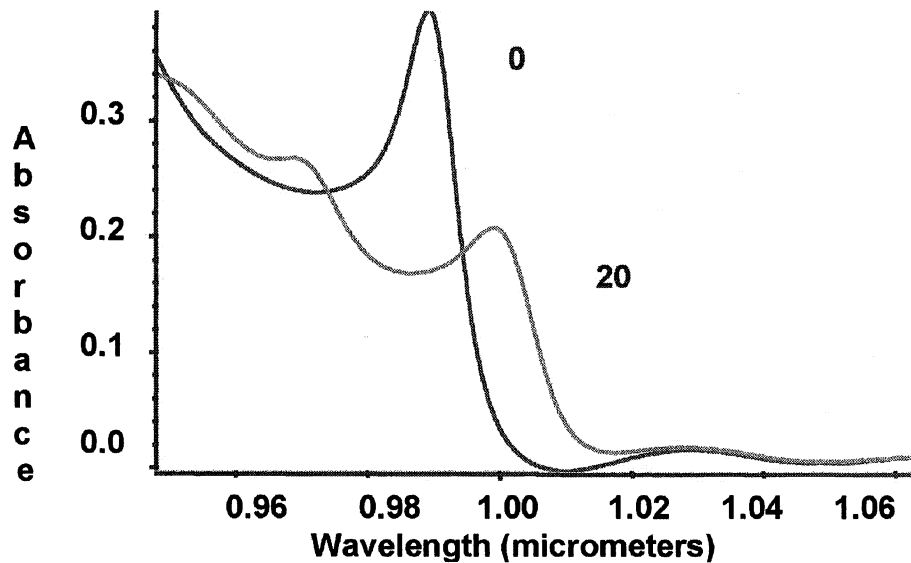

Figure 3. The band-edge optical absorption of an MQW for O and 20 V reverse bias

3.2 MQW Modulator Operating Wavelengths

Because an MQW modulator operates over a relatively narrow bandwidth it must be matched to a particular laser interrogator. The operating wavelength is primarily determined by the composition of the well material. We have examined MQW modulators based on $In_xGa_{1-x}As$ wells grown on a GaAs substrate. As the Indium fraction, x, increases the operating wavelength of the modulator shifts red starting from a wavelength of about 850 nm for a GaAs well to 1060 nm for a $In_{0.26}Ga_{0.74}As$ well. As shown in Fig. 4 the choice of operating wavelength affects not only which interrogating laser can be used but also whether the GaAs substrate is transparent or not. For wavelengths shorter than about 930 nm the MQW modulator must be used in reflective mode or the substrate must be removed.

The operating wavelength cannot be moved arbitrarily red because $In_xGa_{1-x}As$ is not lattice-matched to the GaAs substrate. As the Indium fraction increases so does the strain in the quantum wells. The effect of this to broaden the exciton peak and reduce the extinction ratio of the modulator. For x>0.24, necessary to operate between 1050 and 1060 nm, it is no longer possible to grow good quality quantum wells directly on GaAs substrates. In this case we have used linearly graded buffers to distribute the strain between the wells and barriers[4]. Using graded buffers can extend the operating wavelength of MQW modulators to 1.5 microns, but with decreasing modulator quality. A better solution for 1.5 micron modulators is to change the substrate and grow on InP.
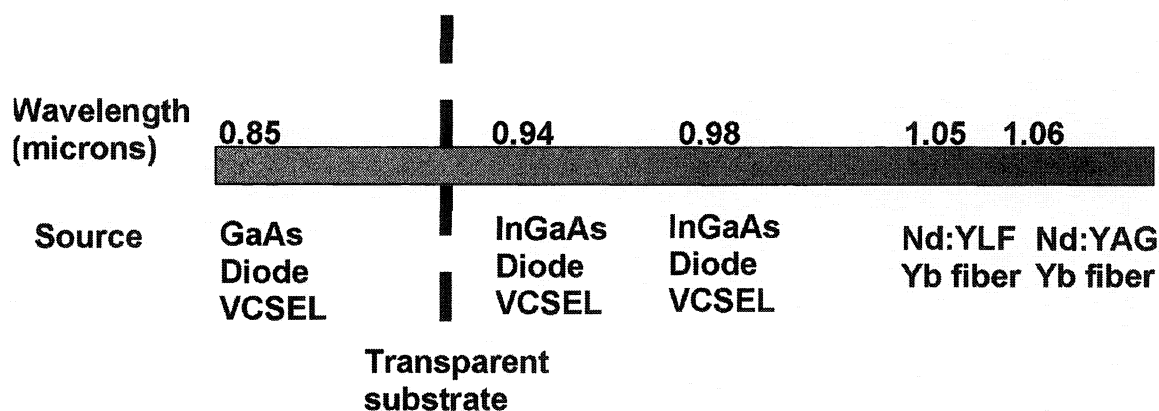
Figure 4. Operating wavelengths of InGaAs/AlGaAs MQW modulators and associated laser transmitters

Because the exciton feature degrades as the operating wavelength moves red, the maximum modulator extinction ratio decreases at longer wavelengths. In choosing an operating wavelength one must balance the performance of the modulator, interrogating laser and receiver as well as any requirements of eye-safety.

We have concentrated on two operating wavelengths to date: 980 nm and 1050-1060 nm. At 980 nm the MQW modulators can achieve higher extinction ratios (about 3:1) than at 1050-1060 nm (about 2:1). Silicon photodiodes also exhibit about twice the responsivity at 980 nm than 1050-1060 nm. Because of the poorer modulator and receiver performance a 1050-1060 nm source must have about 5 times the power of a 980 nm source to close the same link. On the other hand higher power single transverse mode sources are available in the 1050-160 nm band. Currently the highest power single-transverse mode 980 nm sources operate at about 0.5 Watt, but single-transverse mode 1050-1060 nm systems with powers in the tens of Watts are available. For systems that do not require single transverse mode sources 980 nm diode lasers with powers up to tens of Watts are available. Thus in systems which require high power in a single transverse mode to close the link it may be preferable to use 1050-1060 nm modulators (at the cost of much higher power consumption by the interrogating laser). In shorter range systems or ones in which single transverse mode sources are not needed (either because of atmospheric effects or because highly accurate pointing is not available) 980 nm systems may be preferable.

For terrestrial systems, in which eye safety is important, it may be desirable to use a 1.5 micron modulating retro-reflector. At this wavelength modulator performance, source power and receiver performance are all lower than at 1 micron. However, the eye safety limit at 1.5 microns is about one hundred times higher than at about 1 micron. Still it is important to note that 1 micron sources can be eye safe at low enough fluences. For short-range or lower speed modulating retro-reflector links a 980 or 1050-1060 nm system may still be preferable to a 1.5 micron system even for terrestrial links.

3.3 Modulator electrical characteristics

Electrically a large-area MQW modulator acts as a capacitor. Because the optical absorption changes essentially instantaneously in response to the applied field (unlike, for example, liquid crystal modulators) the speed of an MQW modulator is limited by RC time up to very high data rates (exceeding 1 Gbps).

The power consumption of the modulator is generally determined by the power required to charge and discharge the device and has the form

$$P = \eta C V^2 f \qquad\qquad (2)$$

where P is the power consumed, η is a factor that depends on the charging circuit and the communications format used, C is the capacitance, V is the driving voltage, and f is the data rate.

The capacitance of a typical MQW modulator is between 5-10 nF/cm^2. The resistance of the modulator depends on both the driver resistance and the sheet resistance of the semiconductor electrode regions. In practice it is the sheet resistance, which dominates. This can be controlled by the doping and thickness of the semiconductor electrodes as well as the geometry of the metal contacts laid down on the top electrode. In practice resistances between 20-100 Ohms are common. It is also possible to segment the large area device into several "pixels" each of which can be driven independently with the same signal. This has the effect of reducing the capacitance for each pixel and increasing the speed but does not reduce the total power consumption.

The effect of these characteristics is to limit the speed of an MQW modulator for a given aperture. For example a 1 cm MQW corner-cube modulating retro-reflector has an upper speed limit of about 3 Mbps and a 0.63 cm MQW MRR has a top speed of about 10 Mbps. These speeds can be increased somewhat with pixellization, but because the power consumption will not change with pixellization heat removal will become more of an issue. In the last section of this paper we will discuss an alternative MQW MRR that bypasses many of these problems.

The top speed of an MQW MRR is controlled primarily by R and C, but the power consumption is also affected by the driving voltage. MQW modulators work by changing optical absorption in response to an applied voltage. The higher the voltage the higher the optical extinction (up to a saturation value). This sort of modulator is desirable for modulating retro-reflector links because there is a large aperture, no sensitivity to angle or polarization and weaker temperature and wavelength sensitivity than for phase or polarization based modulators. The cost however is a lower extinction ratio than might be achieved with a phase modulator. Typical MQW modulators have extinction ratios between 2:1 and 4:1 with transmission in the on-state of between 30-50%. It is possible to increase the extinction ratio by increasing the thickness of the modulator but this will decrease the on-state transmission and increase the required operating voltage (and hence power consumption). Reducing the drive voltage to reduce power consumption lowers the extinction ratio and thus degrades the optical link.

One way to drop the required operating voltage is with alternative MQW structures. In most of our modulators we have used simple square well structures. In a square well the primary effect of the application of electric field is to shift the energy of the exciton absorption. An alternative structure is the coupled quantum well in which two square wells are coupled by a thin barrier. In a coupled well structure the quantized energy levels split into symmetric and anti-symmetric states that have

different absorption strengths. When a relatively small electric field is applied to a coupled well the symmetry of the structure is broken and the optical selection rules change dramatically. Thus in this sort of structure rather than using the electric field to shift the wavelength at which absorption occurs we use the field to directly change the strength of the absorption. The net effect is a reduction of between 2-3 times in the required operating voltage for a given extinction ratio. Fig. 5 shows the extinction ratio for a square well modulator we have fabricated at 1050 nm with 24V applied. By comparison Fig. 6 shows about the same extinction ratio for a coupled well structure we have fabricated with only 7 V applied. This factor of 3 drop in voltage corresponds to an order of magnitude reduction in power requirement.
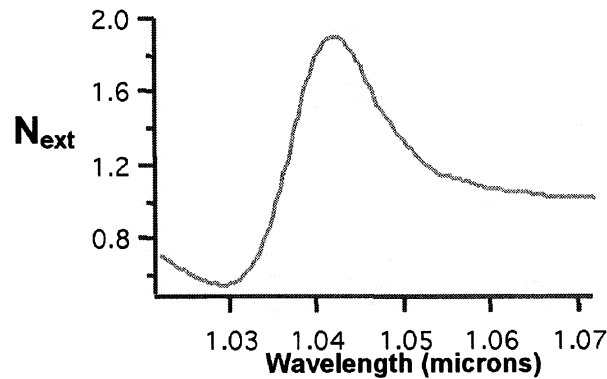

Figure 5. Experimentally measured extinction ratio for a square well modulator with 24 V applied
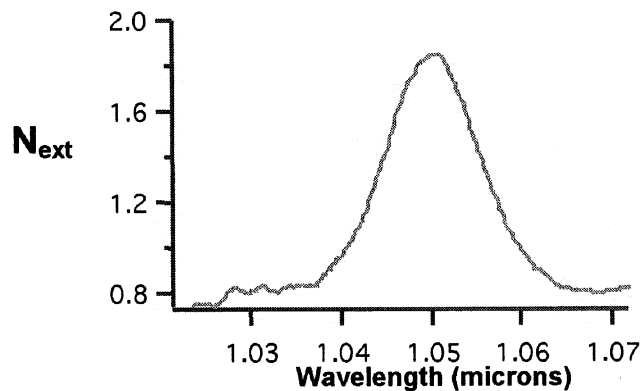

Figure 6. Experimentally measured extinction ratio for a coupled well modulator with 7 V applied

3.4 Modulation Radiation Susceptibility

For space-based applications the ability of an MRR to survive prolonged radiation exposure is of great importance. MQW structures can be expected to be relatively radiation hard due to the lack of an oxide layers. To examine the effects of

radiation on MQW modulators we performed a series of tests in which a set of three identical InGaAs/AlGaAs modulators were exposed to a stepped set of bombardments of 1 MeV protons[5]. One of the modulators was biased to 15V during the bombardment and the other two were left unbiased. After each bombardment the extinction ratio, modulation speed and dark current of the MQW devices were measured.

Table 1 shows the radiation bombardment sequence.

Exposure Number	Cumulative Fluence (cm^{-2})	Equivalent D_d (MeV/g)	Equivalent # of Years in LEO Orbit
1	8×10^{11}	5.40×10^9	3.5
2	4×10^{12}	4.32×10^{10}	28.0
3	8×10^{13}	2.16×10^{11}	140.2
4	1×10^{14}	2.16×10^{12}	1402.4
5	4×10^{14}	5.40×10^{12}	3505.9

Table 1. Radiation tests proton bombardment sequence

No degradation in modulator performance was observed until step 4. Fig. 7 shows the electro absorption spectrum of the MQW modulator before bombardment and after step 4. Even after the last bombardment the modulator extinction ratio declined by less than 25%. Thus MQW MRR devices should be useful even in very high radiation environments. Indeed the simplicity and radiation hardness of these devices should make the especially reliable for many space mission.
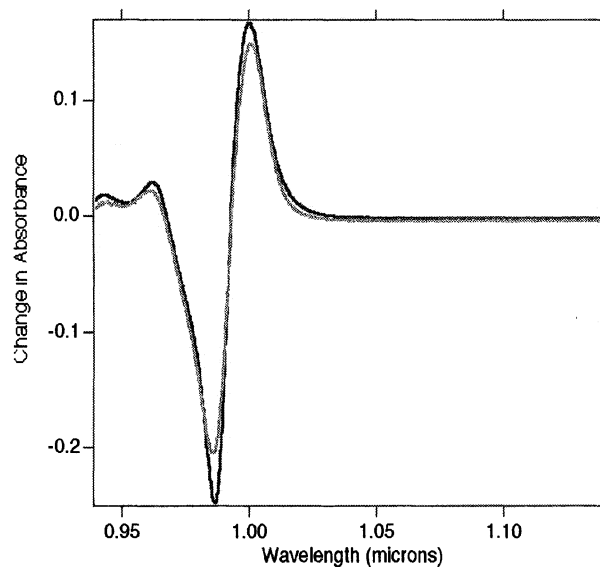

Figure 7. Electroabsorption of an InGaAs/AlGaAs MQW modulator before radiation exposure and after a dosage of 10^{14}/cm^2.

3.5 Modulator temperature dependence

MQW modulators can survive and operate over a very wide range of temperatures (about 4-400K). However, because the modulator works over a restricted optical bandwidth and also because the band-edge of semiconductors shift with temperature, for a fixed laser interrogating wavelength an MQW MRR must be operated in a pre-specified temperature window. Typically around 1 micron wavelength GaAs and its alloys shift their band-gap by about 0.35 nm/¡C. This is shown below in Fig. 8.
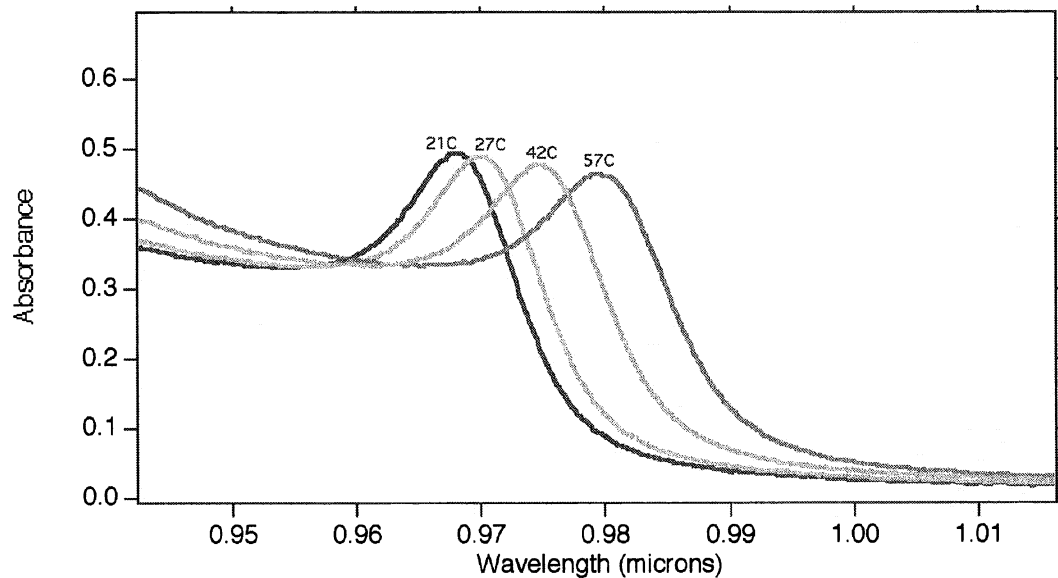

Figure 8. Absorption spectrum of an InGaAs/AlGaAs MQW modulator with no applied voltage for a variety of temperatures.

The bandwidth over which a typical MQW can be operated without dropping its extinction ratio by more than about 20% is around 7-10 nm. Thus there is an approximately 20-30¡C operating window for the device. This range can be extended if a tunable laser interrogator is used since the interrogator can then be adjusted to match the temperature shifted electroabsorption peak.

4. Cat's eye modulating retro-reflectors

As we discussed above the maximum data rate of a corner cube based MQW MRR tends to be limited by the fact that the MQW cannot be too large without being limited in it's modulation rate by it's RC time constant. However, without a large aperture insufficient light is returned to close a high data rate link, except at short range. Thus to realize an MRR system capable of high data rate at ranges exceeding about a kilometer it is necessary to decouple the optical aperture of the retro-reflector from the size of the modulator. This is impossible with MRR systems based on corner-cubes, since the modulator must cover the entire entrance aperture.

However, a corner-cube is not the only kind of retro-reflector. An alternative kind of retro-reflector is the cat's eye. Cat's eye retro-reflectors come in a variety of forms but generally include at least one lens and one reflector, which may be curved. A

common form of a cat's eye retro-reflector is shown in Fig. 9. A cat's eye is useful for MRR's because it incorporates a focus. Thus if the modulator can be placed at the focus it can maintain a small size while the optical aperture remains large. However, simply placing a single small MQW modulator at the focus of a cat's eye will not produce a useful system. This is because if the MRR must cover any finite field of view the focal spot will move. In fact for a typical cat's eye system the size of a modulator large enough to cover a 30 degree field of view is about 30% of the optical aperture. While this size reduction would increase the maximum modulation rate by a factor of 10, it is possible to do better still.
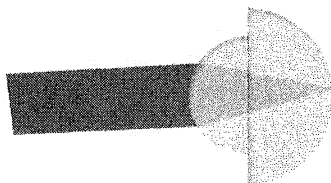

Figure 9. A cat's eye retro-reflector

As mentioned above MQW modulators take the form of PIN diodes. Thus in addition to acting as modulators they also act as photodetectors. When under DC reverse bias the current running through the MQW is proportional to the optical flux upon it. Typical responsivities vary between 0.1-0.3 A/W depending on the MQW structure and the reverse bias. We can make use of this photosensitivity to increase the maximum data rate of a cat's eye MRR and decrease its power consumption. If we make a pixellated MQW array with sufficient size to cover the focal plane of the cat's eye then by periodically monitoring the photocurrent in each pixel we can determine at any given time which pixel is illuminated and drive only that one. Which pixel is illuminated will change slowly as the relative angle between the platform carrying the cat's eye and the interrogating laser changes. A pixellated cat's eye MRR such as that shown in Fig. 10 could have an optical aperture of several centimeters while allowing modulation rates of hundreds of Mbps. It is important to note that the size and the number of pixels in such a structure have no effect on the retro-reflection accuracy. Unlike electronic beam steering systems based on spatial light modulators a cat's eye MRR is not a diffractive system, but a bulk refractive system. The purpose of the pixellization is only to decrease the modulator capacitance which must be driven.
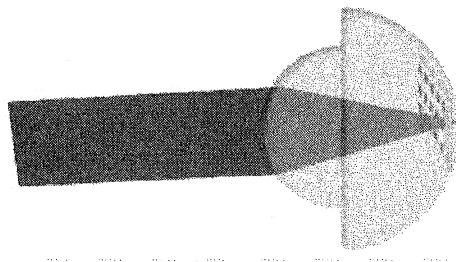

Figure 10. A cat's eye modulating retro-reflector

Cat's eye MRRs based on optics such as those shown in Fig. 10 may not be optimal. This is because the simple two element, spherically symmetric cat's eye shown has a large amount of spherical aberration which will reduce the power returned in a

link. An optimal cat's eye MRR is an optical design problem with many possible solutions. One of our preliminary designs uses 4 elements and can produce diffraction-limited retro-reflection over a 35 degree field. The design has a 2.5 cm aperture and an 8 mm focal plane. If we assume a rather coarse pixellization of 8x8 then a 1mm MQW pixel could be driven at data rates of about 100 Mbps while consuming less than 50 mW. At the same time the light returned by such a system would be about 100 times greater than a corner cube system covered by an equivalent 8 mm monolithic MQW.

Cat's eye MRR systems are currently under development in our laboratory. While they are more complex than corner-cube systems they do have the potential to push the data rates of MRR systems up to levels more typical of conventional optical communications systems.

5. Conclusions

Modulating retro-reflectors have been considered and demonstrated for optical communications for many years. While the idea is conceptually simple the components for practical systems including reliable lasers and pointer-trackers for the interrogator and fast modulators for the MRR have only recently become available. MRR systems do not replace conventional free-space optical communications systems; indeed they rely on them. As free-space optical communications becomes more prevalent and transmitters are placed on more platforms, MRR systems will enable smaller platforms, unable to carry a conventional transmitter, to become part of the free-space optical communications network.

ACKNOWLEDGEMENTS

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